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ABSTRACT

A method of incorporating statistically designed fractional factorial experiments into lithographic process simulation software (PROLITH/2) has been used to determine input factor interrelationships inherent within a lithographic process. Rotatable Box-Behnken designs with 3 centerpoints were utilized for the experiment. The response surface methodology (RSM) approach was used to analyze the influence of independent factors on a dependant response, and optimize each process. A "method of steepest ascent" was utilized to produce first-order models, which were verified by lack of fit testing. As optimum operating points were approached, a second-order model was fitted and analyzed. A series of experiments studying the effects of prebake, exposure, post-exposure bake, and development on critical dimension and profile in PROLITH/2 produced response surfaces relating each main factor effect as well as non-linear and interaction effects. Additionally, experiments were conducted to study effects of numerical aperture, coherence, feature size, defocus, and flare on aerial image contrast. Process optimization for the target response value as well as process latitude as it relates to all factors simultaneously was then possible through use of the response surface.

2. RESPONSE MODELLING FOR LITHOGRAPHIC PROCESSING

The understanding and control of a lithographic process is clearly of critical importance for the manufacture of integrated circuits. In order to maintain the requirements of high resolution lithography, parameters such as sidewall angle, linewidth variation, and image contrast must be well controlled to produce features of maximum integrity. A factorial design approach to analyzing and optimizing a lithographic process allows creation of process response surfaces, relating input factors to critical response parameters (response surface methodology or RSM). In RSM, multi-dimensional response surfaces are possible. A two-dimensional response surface may be graphically represented, with x and y axes being factor planes and z being the response. Contours of constant expected response then yield the response surface. Response surface analysis can then be done on the fitted surfaces.

Response surface methology is a tool often applied to pilot plant operations, or at the onset of process development to determine optimum operating conditions and to incorporate process tolerance into manufacturing. The application of this technique to process simulation becomes evident as simulation packages and tools are being incorporated into process development and enhancement. Statistical

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software packages have been developed to ease the computational requirements of statistical design and analysis of experiments. Packages such as RS/1 have incorporated response surface methology, removing some of the involved computation from the experimenter. Lithographic modelling and simulation packages such as PROLITH/2 have evolved into powerful process development and optimization tools for microlithographic applications. The combination of these two development tools allows one to gain understanding about the physical machanisms and relations existing in a lithography process and determine the region within a factor space where operating specifications are satisfied or optimized.

Unlike many RSM problems, the form of the relationship between factors and responses in the case of simulated processes is generally understood. Thus, finding a functional relationship between responses and independent factors is straight-forward. A model is determined which approximates the response relationship within a region of interest. The response is modelled first by a first-order polynomial of the linear form:

$$R = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k + \varepsilon$$

If a first-order linear polynomial does not model curvature existing in the response, a higher-order polynomial is sought:

$$R = \beta_0 + \Sigma \beta_i x_i + \Sigma \beta_{ij} x_i^2 + \Sigma\Sigma \beta_{ij} x_i x_j \ldots + \varepsilon$$

A method of least squares regression analysis is utilized to estimate parameters within a model. In order to accomplish this, a designed experiment is carried out, and the analysis of variance of the experiment helps identify important factors and relate factors to the response. Multiple linear regression is utilized if first-order models suffice in approximating responses, or an orthogonal polynomial approach may be carried out to compute polynomial effects of factors. These regression approaches not only allow point estimates, they make it possible to obtain interval estimates on parameters.

After determining model parameters, a method of model adequacy checking must be employed to determine adequacy of the least squares fit. Analysis of residuals through means such residual vs. fitted values plots or normal probability plots will determine adequacy of fit, while a "goodness of fit" test will determine if approximation is valid.

Once a model and parameters are fitted, response surface analysis is carried out on the fitted surface. Analysis of this surface will yield results approximating those carried out in the actual system. This demonstrates the power of the RSM approach, in that once a suitably designed experiment has been carried out, analysis of factor combinations at levels not experimentally run can be performed. Multiple responses can be analyzed simultaneously and provide for determining optimal process conditions under various constraint conditions.

3. RESPONSE SURFACE DESIGN

In order to fit model parameters for a second-order model, a three level experimental design must be used. Rotatable designs are most suitable, with common types being central composite and Box-Behnken designs. This investigation utilized Box-Behnken designs, with four factors, two responses for resist modelling and five factors, one response for aerial image modelling. Factors for resist modelling were prebake temperature, exposure energy, postbake temperature, and develop time. Responses were critical dimension (1.25 micron nominal) and side wall angle. A KTI resist was chosen for investigation in PROLITH/2. Factors studied for aerial image modelling were numerical aperture, degree of coherence, nominal linewidth, defocus, and flare. The response studied was aerial image log slope. These designs yielded 27 and 46 process runs, respectively. Least squares analysis of variance showed no evidence of lack of fit for models for each factor. An estimate of the standard deviation of the residuals was determined using a root mean square error statistic (R-squared), which proved minimal. Response surfaces of each two-factor combination were created and are included as Figures 1 and 2, for aerial image and resist process experiments.

4. PROCESS OPTIMIZATION

As seen in Figure 1, every combination of two factors have been plotted as aerial image log slope response surfaces. The physical mechanisms determining image formation can be evaluated for each two factor combination, with other factors fixed (at central values in this case). Clearly, optimum image contrast is not linearly related to input parameters, and non-linearity increases as diffraction limitation of the system is approached. (It should be pointed out that no confidence intervals have been incorporated into the response surfaces for input factors). For any chosen fixed set of values for factors not plotted, a different set of response surfaces would be produced. Simple two-factor relationships can be easily examined, such as the numerical aperture and defocus related effect on aerial image.
Similar analysis can be conducted on the set of response surfaces in Figure 2. In this case, though, two responses have been measured, which add additional possibilities for process understanding. In order to study response effects, constraints need to be determined for each response, or, in the case of the two-response experiment, one response could act as a constraint on another. Final process tolerance or specification would determine process windows, or the performance of device parameters further along in the IC process could force a process window, which then could be optimized. Since final device performance and reliability is the ultimate goal, this technique can be carried on through an entire processing sequence. The two process stages studied here, namely the aerial image formation and resist interaction process, account for initial stages in an entire fabrication sequence. Any sequence of process events, inherently interrelated, could be better understood and optimized for using a RSM approach. If simulation tools are available for those events, physical mechanisms can be understood. The RSM approach along with such physical models can be extended to include real process variations.

5. CONCLUSIONS

Utilization of this RSM technique with process simulation allows for optimization of lithographic processes before they are incorporated into the manufacturing environment. Photolithography steps were simulated using PROLITH/2, studying a) the effects of NA, coherence, linewidth, defocus, and flare on aerial images and b) the effects of prebake, exposure, postbake, and develop on critical dimension and sidewall angle. Process windows were then determined from response surfaces, based on process constraints or specifications. This method proves useful for understanding of interrelationships within factor sample spaces, and optimizing circuit manufacturing.

6. REFERENCES

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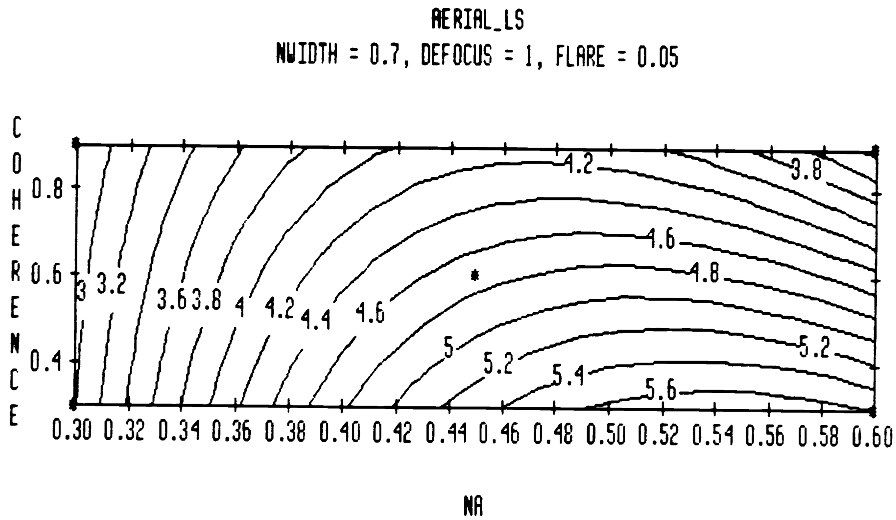
Figure 1 a-c


AERIAL_LS
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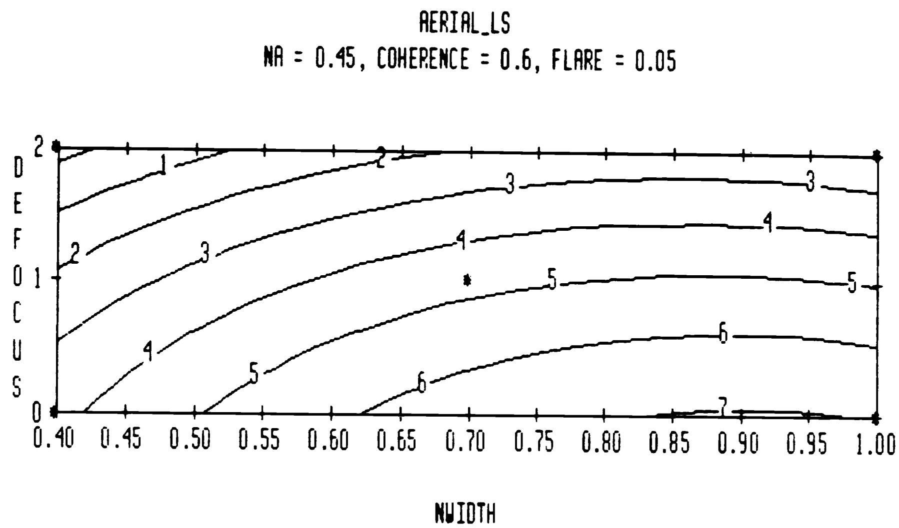
COHERENCE
0.8
0.6
0.4
3 3.2 3.6 3.8 4 4.2 4.4 4.6
5 5.2 5.4 5.6
4.2 3.8 4.6 4.8 5.2
0.30 0.32 0.34 0.36 0.38 0.40 0.42 0.44 0.46 0.48 0.50 0.52 0.54 0.56 0.58 0.60
NA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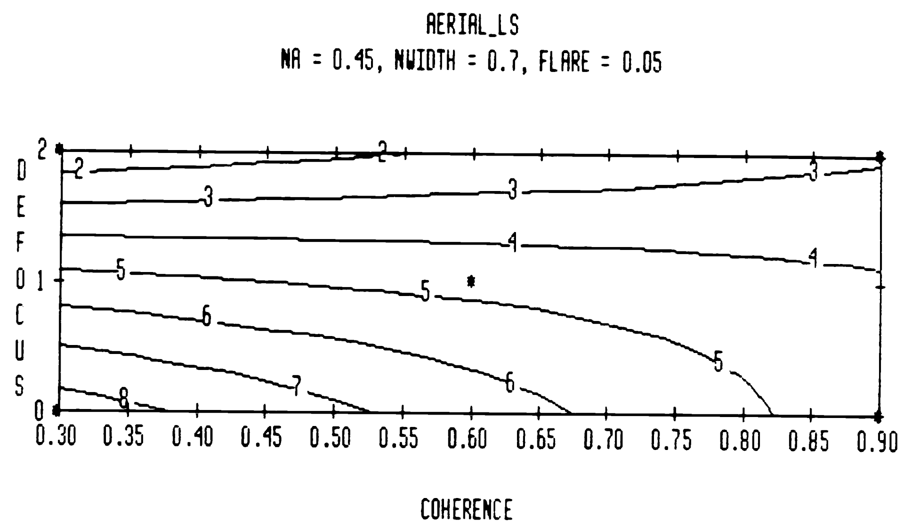
1
0
1 2 3 4 5 6 7
0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75 0.80 0.85 0.90 0.95 1.00
NWIDTH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DEFOCUS
2
1
0
2 3 4 5 6 7 8
0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75 0.80 0.85 0.90
COHERENCE

Figure 1 d-f

AERIAL_LS
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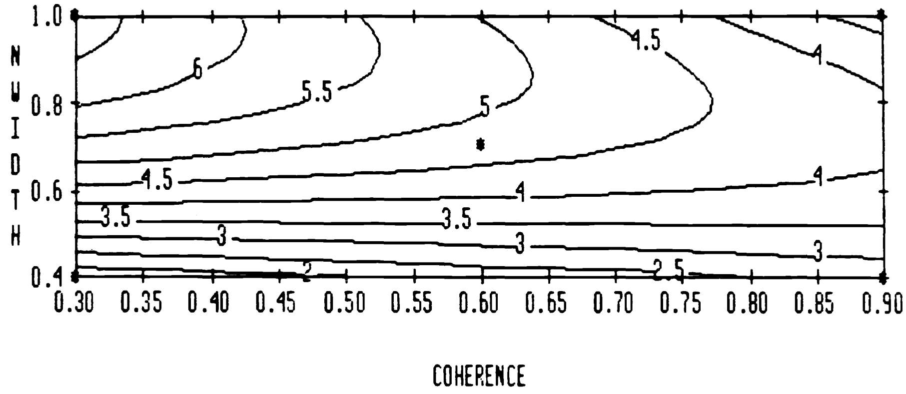

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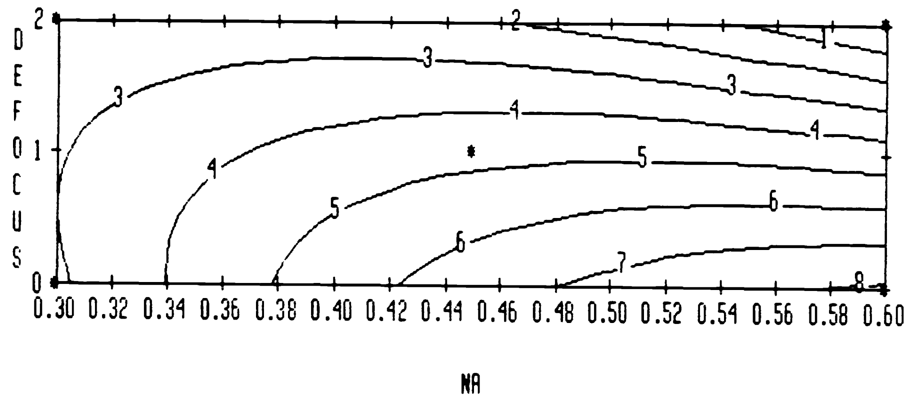

AERIAL_LS
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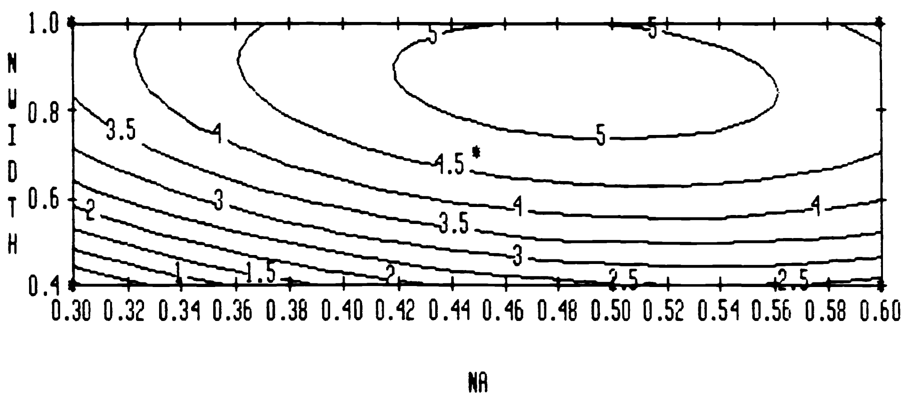
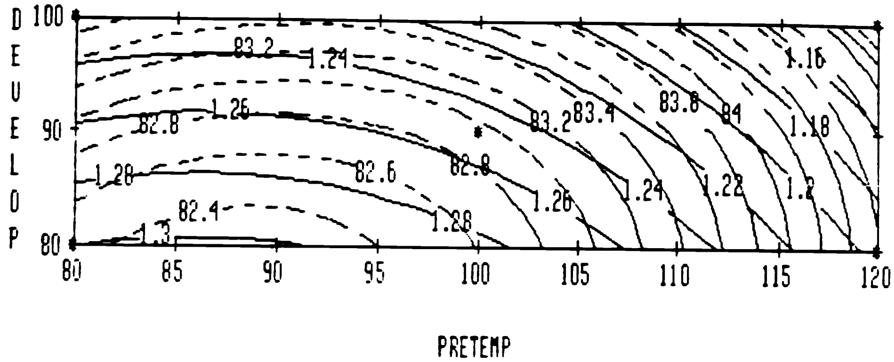
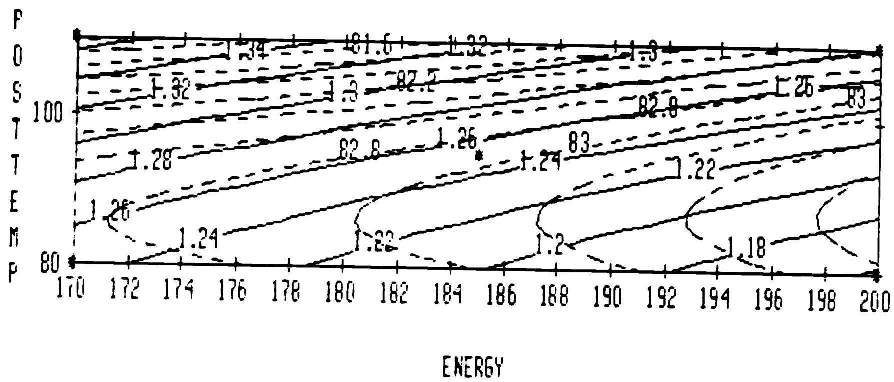


Figure 2 a-c

CD, PROFILE
ENERGY = 185, POSTTEMP = 95



CD, PROFILE
PRETEMP = 100, DEVELOP = 90



CD, PROFILE
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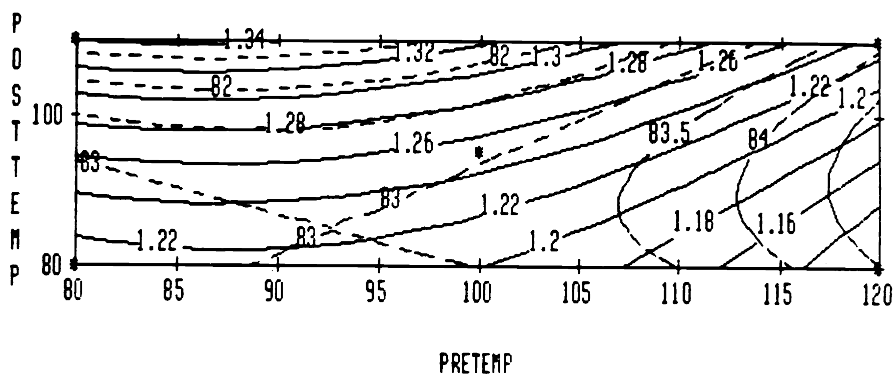
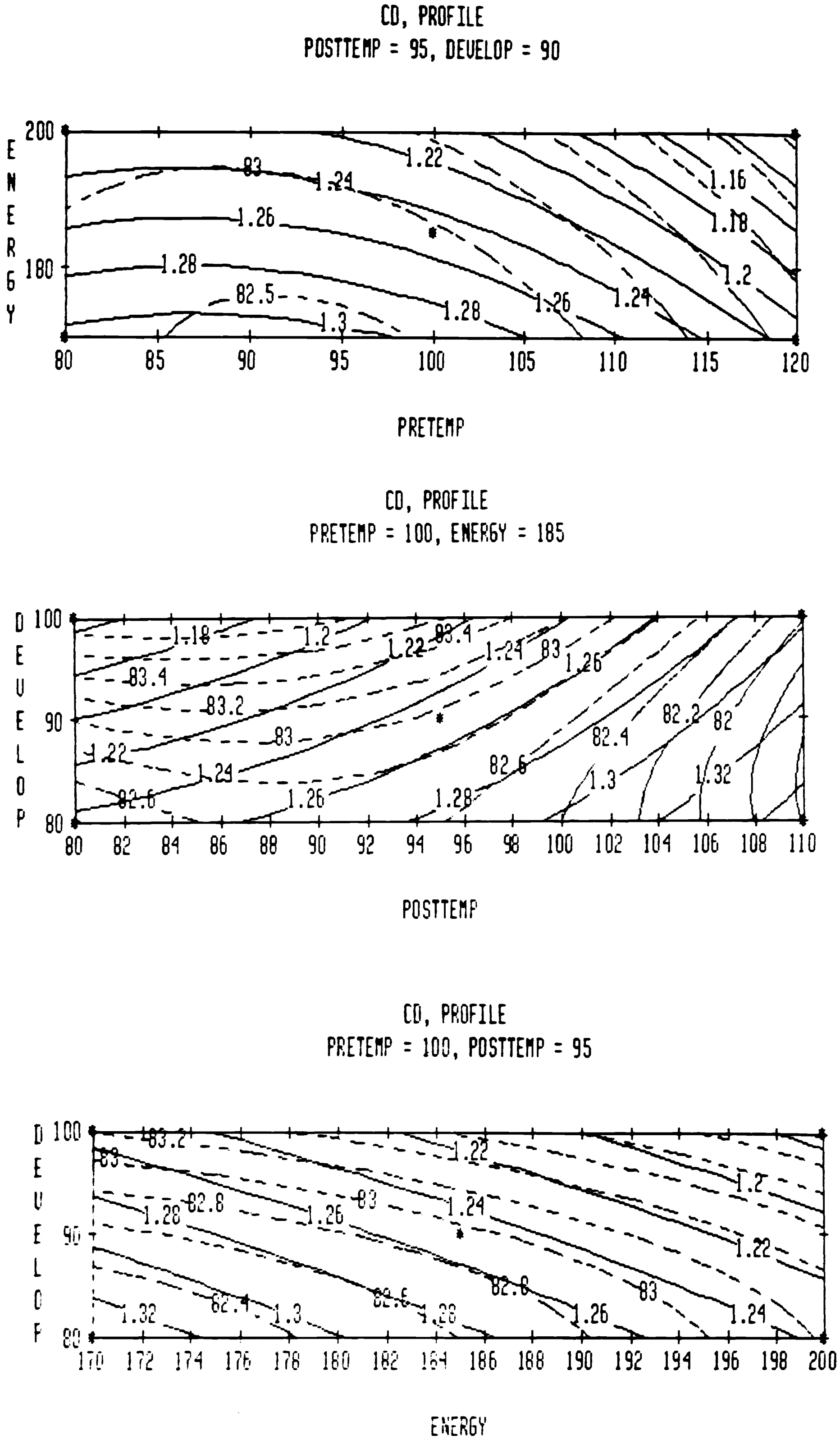


Figure 2 d-f



CD, PROFILE
POSTTEMP = 95, DEVELOP = 90
ENERGY
200
180
80 85 90 95 100 105 110 115 120
PRETEMP
CD, PROFILE
PRETEMP = 100, ENERGY = 185
DEVELOP
100
90
80
80 82 84 86 88 90 92 94 96 98 100 102 104 106 108 110
POSTTEMP
CD, PROFILE
PRETEMP = 100, POSTTEMP = 95
DEVELOP
100
90
80
170 172 174 176 178 180 182 184 186 188 190 192 194 196 198 200
ENERGY